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Nutrient transport characteristics of livestock manure in a farmland

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Abstract

Background: Livestock excretions containing high concentration of nutrient, pig liquid fertilizer, and cattle manure were applied to agricultural land. The characteristics of nutrient transport were examined in surface runoff and groundwater by an artificial rainfall event at real scale field site. Also, the effects of the artificial rainfall event on the characteristics of residual soil after the rainfall and phosphorus adsorption capacity were evaluated in the lab.

Results: As results from the field experiments, nitrogen concentration was decreased by the repeatable precipitation in surface runoff, but the nitrate concentration in groundwater was gradually increased by biological metabolism, especially with pig liquid fertilizer. Phosphorus was mostly adsorbed into the soil, and its reduction was affected by the soil drainage due to surface runoff in summer. The adsorption capacity of the phosphorus via a jar test was determined as 0.7 mg P/kg of soil.

Conclusion: The soil adsorption capacity would be an important factor for the optimum level of nutrient application that is required for agricultural performance and minimal environmental impact.

Keywords: Cattle manure, Nitrogen, Phosphorus, Pig liquid fertilizer, Surface runoff

Introduction

Livestock excretions contain strong nutrient matters, nitrogen and phosphorus, that could be applied to agricultural land as a fertilizer for the growth of organisms. Phosphorus is especially an essential nutrient in plants and has important functions such as storage and transfer of energy (Zaimes and Schultz 2002). Land application of the livestock excretions not only supplies nutrients to the crop plants but is also accumulated in the land. Excessive nutrients remaining on the soil surface lead to loss of the nutrients to the watershed by spring snow melting or intensive rainfall events (Little et al. 2005). The nutrient loss results in the growth of green algae and eutrophication, when nutrients are directly discharged to a stream from the surface runoff (Correll 1998). Livestock excretion has been issued as a difficult non-point source pollutant that needs to be controlled in the watershed, and agricultural management of the livestock excretions should be performed to protect the stream water quality based on potential loss of nutrients due to surface runoff (Sharpley et al. 2001).

Fertilizer application loading is usually limited by the nitrogen requirement for crop growth rather than by phosphorus (Sharpley et al. 2001). Therefore, phosphorus is mostly overdosed into the agricultural land resulting in accumulation in the soil. Phosphorus has low water solubility and more potential to be runoff by soil erosion than nitrogen during a rainfall event (Little et al. 2005). Moreover, the runoff characteristic of the nutrients could differ according to the manure source applied (Kleinman et al. 2002) and its rate of application (Kleinman and Sharpley 2003). In this study, when pig liquid fertilizer and cattle manure were used as a fertilizer in the agricultural land, the effects on the soil and groundwater were analyzed. A field site was constructed, and the runoff characteristic in surface and groundwater by the applied artificial rainfall was examined. A lab scale column test and jar test were also performed to identify the capacity of phosphorus adsorption in the soil.

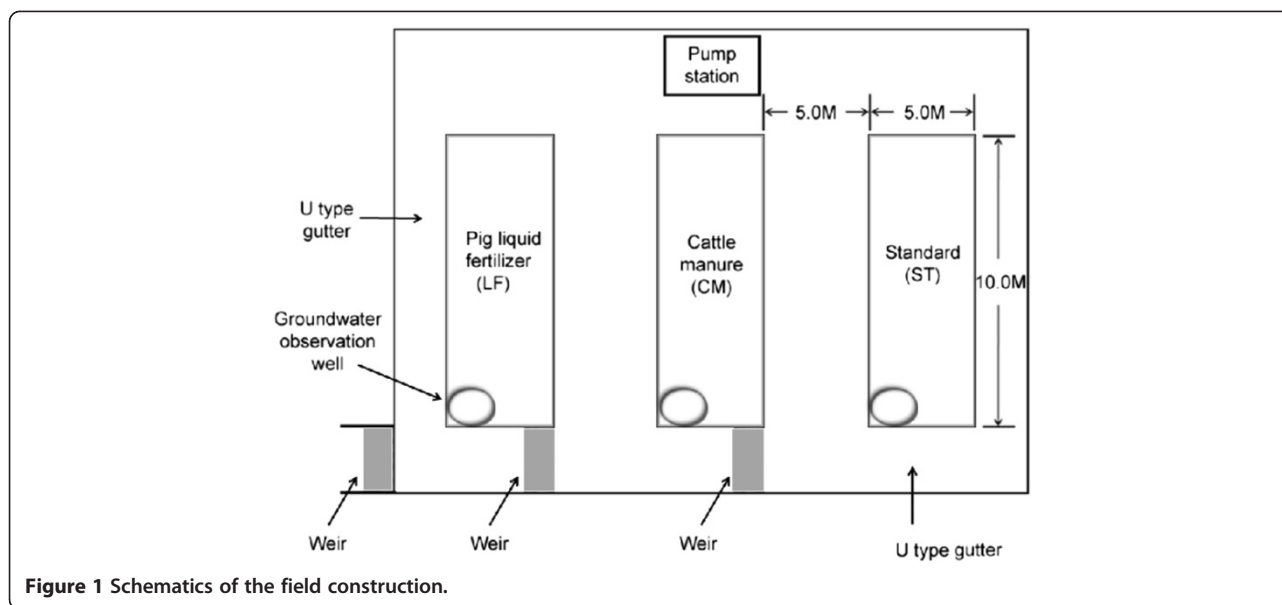
Methods

Field construction

The test areas as shown in Figure 1, namely the standard (ST), cattle manure (CM), and pig liquid fertilizer (LF)

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areas, were constructed in 5×10 -m sites on an empty farmland in Korea ($36^{\circ}19'45.71''$ latitude and $127^{\circ}37'16.91''$ longitude). The test areas were spaced at 5 m apart to avoid interference. The test sites had a U-type gutter with a 15-cm depth and a 1.7° to approximately 2.3° slope for the sampling of surface runoff from an artificial rainfall event). The runoff was collected from the gutter. For the field tests, it was hypothesized that the total amount of rainfall is captured as groundwater, except for the surface runoff.

Characteristics of soil

In the field test, the textural class was coarse sandy soil (84.5%). The remaining soil consisted of 13.6% of gravel and 1.9% of silt and clay. The coefficient of permeability was determined as 2.86×10^{-4} cm/s in the ST area, 2.43×10^{-4} cm/s in the CM area, and 5.25×10^{-4} cm/s in the LF area by the AQTESOVE model (Bouwer and Rice 1976; Cooper et al. 1967). Even though the same soil was used in the column test, the textural class was changed to fine texture during the repeated rainfall event (1.6×10^{-2} to 3.71×10^{-3} cm/s). The pH and bulk density of the soil were measured as 6.7 and 2.4 ton/m^3 , respectively. The cationic exchange capacity was 65 meq/100 g which belongs to the natural soil range.

Resources

Cattle manure was collected from a pile separated from cleaning water in a cattle farm, and pig liquid fertilizer was collected from anaerobic digestion effluent in a pig farm near the field site. The livestock excretions were sprayed onto the test site as $900 \text{ kg}/50 \text{ m}^2$ of cattle manure and $1,200 \text{ L}/50 \text{ m}^2$ of pig liquid fertilizer (210 kg N/ha/year). These quantities were based on the

standard rate of 200 kg N/ha/year according to the European Union (Reindl 2007). The same ratio of the resources was applied to the column test. The initial concentration of the resources was analyzed in chemical oxygen demand (COD), total nitrogen (TN), and total phosphorous (TP). Table 1 shows the characteristics of the cattle manure and pig liquid fertilizer for the field test and column test.

Characteristics of soil with nutrient applied

The soil characteristics were analyzed before applying fertilizers, after applying fertilizers in spring, and after harvesting in the fall for each test area (Table 2). The soil before applying fertilizers was characterized as $1,520 \text{ mg/kg}$ of TOC, 2.3 mg/kg of $\text{PO}_4\text{-P}$, 65 mg/kg of TN, and 18.3 mg/kg of TP. Compared to the organic and nutrient concentrations between after applying the fertilizers and after harvesting, TOC was increased by about 12% in CM and 21.4% in LF; however, the nutrient concentrations tended to decrease, resulting from utilization by crop (corn) growth or from stream to groundwater runoff due to the rainfall event.

Table 1 Characteristics of the resources

| Parameter | Field test | | Column test | |
|-----------|------------------------------|-----------------------|------------------------------|-----------------------|
| | Pig liquid fertilizer (mg/L) | Cattle manure (mg/kg) | Pig liquid fertilizer (mg/L) | Cattle manure (mg/kg) |
| COD | 24,400 | 121,300 | 21,600 | 90,400 |
| TN | 4,087 | 5,310 | 1,010 | 5,950 |
| TP | 409 | 2,110 | 102 | 2,029 |

Table 2 Soil characteristics according to resources applied at initial, before, and after cultivation at each test area

| Item (mg/kg) | Standard area | | | Pig liquid fertilizer area | | | Cattle manure area | | |
|--------------------|---------------|-------|-------|----------------------------|-------|-------|--------------------|-------|-------|
| | a | b | c | a | b | c | a | b | c |
| TOC | 1,433 | 1,312 | 1,586 | 1,514 | 4,312 | 5,483 | 1,612 | 6,012 | 6,832 |
| PO ₄ -P | 2.4 | 3.1 | 1.6 | 3.2 | 15.3 | 3.7 | 1.3 | 24.6 | 13.1 |
| TN | 72.1 | 65.4 | 31.2 | 64.3 | 205.3 | 108.7 | 58.6 | 366.7 | 132.7 |
| TP | 18.2 | 28.2 | 15.9 | 16.4 | 53.0 | 17.6 | 20.0 | 84.2 | 24.8 |

a, before applied; b, before cultivation; c, after cultivation.

Field test

Field tests were seasonally (spring to fall) conducted at the three different test areas with different resources for 8 months. During the test, corn was cultivated at the test area (LF and CM) to set it as a real agriculture farm. Artificial rainfall was applied with about 820 L of groundwater at a rainfall intensity between 9 and 30.4 mm/h and was monitored for 24 h for each study. The artificial rainfall experiments were conducted when the rainfall does not affect to the experimental results. The interval between the artificial rainfall and the nearest rainfall was about 3 weeks. Surface runoff and groundwater samples were collected from each test area and were analyzed in COD, total suspended solid (TSS), TN, TP, NO₃-N, and PO₄-P.

Column test

Three 40-cm-long columns with a 28 cm² of projected area including the top and bottom open holes were prepared for an off-site test in our lab. A small surface area was used for the uniform distribution of resources. The active volumes of each test were 588 cm³ (21-cm height) for ST, 644 cm³ (23-cm height) for LF, and 756 cm³ (27-cm height) for CM. One liter of water to corresponding rainfall was added from the top to the bottom of each column six times. After the column test, residual soil was collected at 5 points (at the floor and at 5, 10, 15, and 20 cm from the top), and the nutrient concentration remaining was analyzed.

Study of adsorption capacity

Phosphate adsorption capacity was determined by a jar test with different initial concentrations of phosphate (0.05 to 2 mg/L) at room temperature. Fifty grams of soil and 100 mL of PO₄³⁻ solution were added into each 250-mL Erlenmeyer flask. Adsorption capacity (mg PO₄³⁻/kg of soil) was calculated from the decrease of the solution concentration. Liquid fertilizer was examined for the soil retention capacity by the same method. Different gram quantities of soil (100, 150, 200, 250, and 300 g) and 300 mL of the pig liquid fertilizer were applied.

Soil and groundwater sampling

Surface soil (below 20 cm from the ground) was collected to analyze the initial soil characteristics. A well was constructed at each test area to a depth of 7 m considering the groundwater level, with a diameter of 150 mm including a water gauge pipe of 50 mm. Coarse sand was filled between the well and the pipe, and each well was covered with a cap. Five liters of groundwater was collected using a high-performance pump (model 77600-62, Masterflex, Cole-Parmer, Vernon Hills, IL, USA) at every test.

Analysis

Liquid samples were analyzed for total organic carbon (TOC; Walkey-Black method), TN (Kjeldahl method), and TP (ascorbic acid method, 880 nm) using UV-1601 spectrophotometer (Shimadzu Corporation, Nakagyo-ku, Kyoto, Japan) in accordance with the Standard Methods. Ammonia, nitrate, and phosphate were analyzed using ion chromatograph (DX-120, Dionex, Sunnyvale, CA, USA). The liquid samples were filtered by a membrane filter with a pore size of 0.45 µm before the instrument analysis. Soil samples (initial soil and after drainage in the column test) were also analyzed in pH (Cole-Parmer), TOC, TN (Kjeltec 2100 distillation unit, FOSS Analytical A/S, Hillerød, Denmark), and TP by the Standard Methods. All experimental analyses were conducted in triplication, and averaged values were presented.

Results and discussion

Nutrient losses by rainfall event

The characteristics of nutrient losses were examined by applying an artificial rainfall event in the on-site field over a period of 8 months (spring to fall) depending on the type of livestock excretion applied. When LF or CM was used as a fertilizer, the nutrient loss by surface runoff and leaching to groundwater were monitored. Results of nitrogen variations in surface runoff and groundwater are shown in Figure 2. In the LF area, the total nitrogen concentration was significantly decreased by surface runoff, while nitrate concentration was gradually increased in groundwater via repeatable artificial rainfall events resulting in biological metabolism by

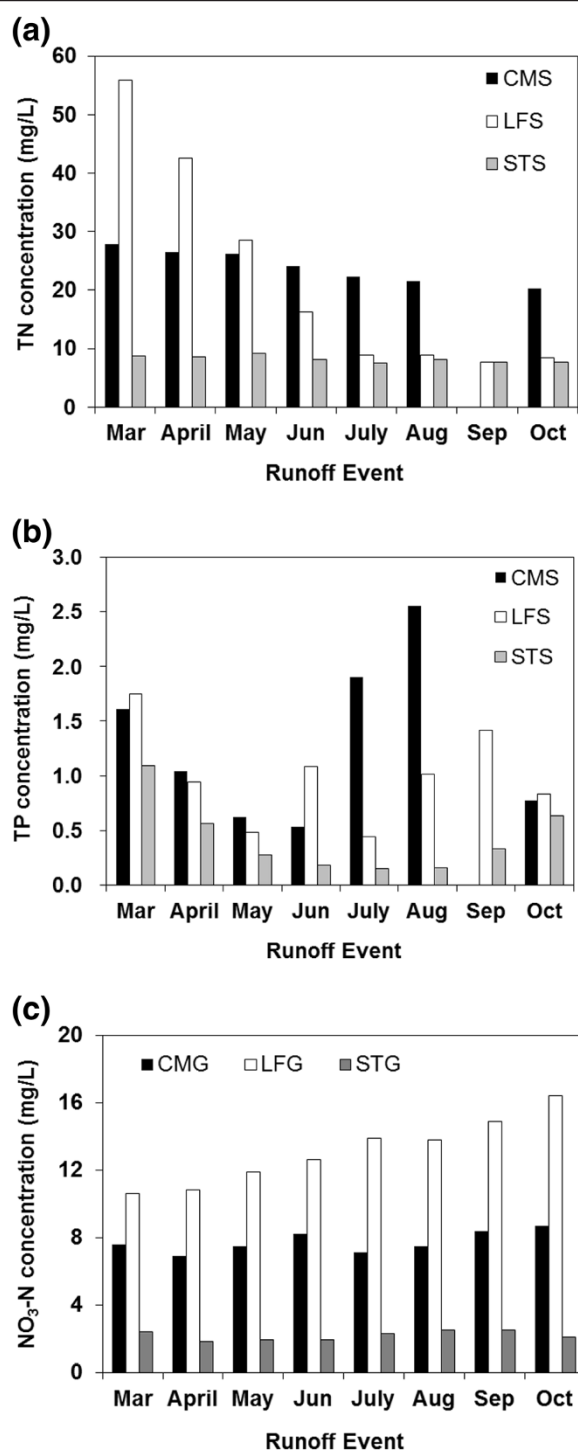


Figure 2 Total nitrogen, phosphorus, and nitrate concentrations in surface runoff (S) and groundwater (G). ST, standard; LF, pig liquid fertilizer; CM, cattle manure.

nitrifiers in the soil and groundwater (USEPA 1993). In the CM area, the total nitrogen concentration from surface runoff was slightly decreased, and the nitrate concentration variation in groundwater remained at around 7 to 8 mg/L, irrespective of the rainfall event. This is because of the high physicochemical property of the solid manure compared to the liquid manure. In other words, the cattle manure is heavy and does not easily penetrate the soil, with a lower degradation rate of nitrogen from ammonia to nitrate compared to the liquid fertilizer.

A comparatively high concentration of phosphorus was detected in the surface runoff in July and August (Figure 2b). The phosphorus loss by surface runoff was focused at an intensive rainfall period (summer). Even though a similar intensity of artificial rainfall was applied for each test, the soil condition could differ according to the actual rainfall in the field site. (McDowell and Sharpley 2002) reported that antecedent soil moisture affects P transport. During the observation period, the SS concentration at the LF and CM test areas varied from 316 to 1025 mg/L for the non-precipitation and precipitation periods. The phosphorus concentration was higher by about 2.1 times for the precipitation period. This condition was more prominent at the CM test area than at the LF test area due to the characteristics of the solid form of the CM.

The phosphorus concentration in groundwater at each test field was monitored as approximately 0.1 mg/L with about 0.33 mg/L maximum and 0.05 mg/L minimum distributions. The influence of phosphorus was lower than that of nitrogen due to rainfall in groundwater. However, in contrast to nitrogen, phosphorus is barely degraded by bacteria. Most of the P was residual in the soil (51% for LF and 60% for CM from the mass balance of the nutrient). Therefore, phosphorus absorbed in the soil would be continuously run off or leached from the rainfall event,

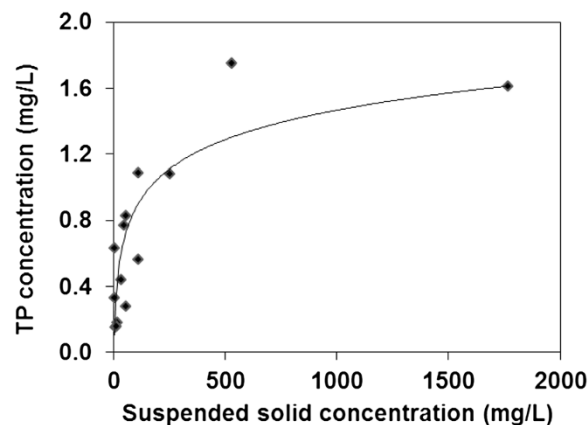


Figure 3 Phosphorus losses versus suspended solid by surface runoff based on field test.

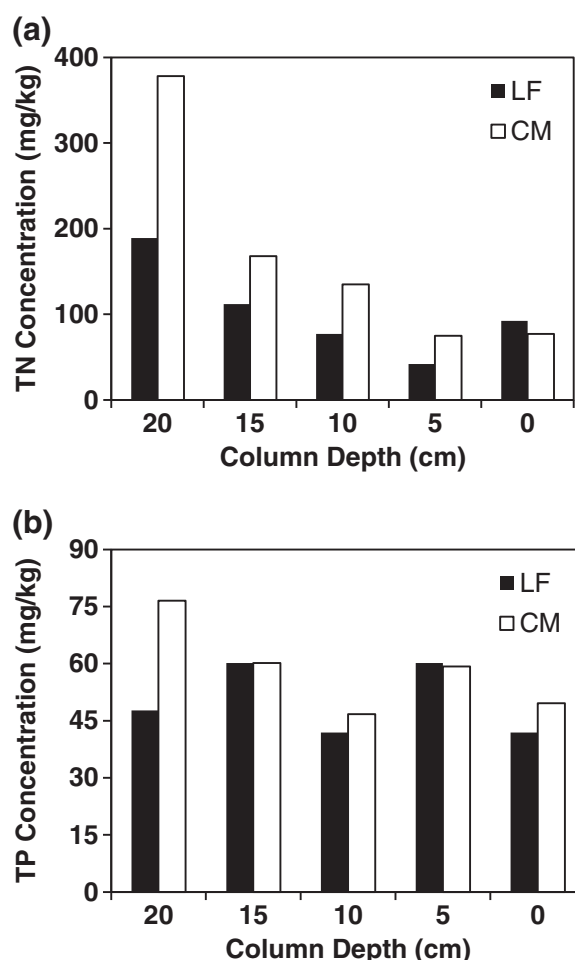


Figure 4 TN (a) and TP (b) variations in the residual soil. At different column depths based on lab test.

thereby the management of P as a contaminant is especially required for protecting the watershed quality.

Phosphorus loss by surface runoff could also be affected by runoff volume, soil loss, the type of P (particulate or soluble), and soil surface characteristics (Udawatta et al. 2004). In this study, P loss was relatively more correlated with the soil drainage from the rainfall event than with a biological reaction. The relationship between the suspended solid and phosphorus variation is presented in Figure 3. As the concentration of SS by surface runoff increased, the P loss was also increased. A similar result was also presented in (Udawatta et al. 2004) study, whereby TP loss is related to the sediment loss.

Characteristics of residual soil after rainfall

Off-site column tests were performed, and the characteristics of the nutrient transport in the residual soil were analyzed. The results in Figure 4 show the nutrient concentrations remaining at the different column

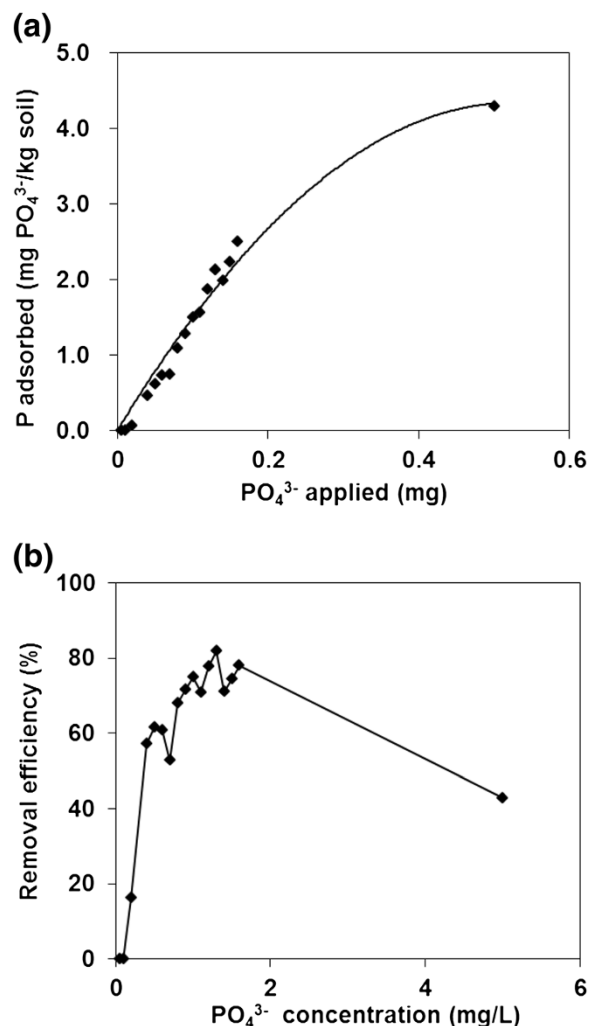


Figure 5 Phosphate adsorption and removal efficiency.

Phosphate adsorbed per kilogram of soil (a) and removal efficiency (b) depending on the phosphate concentration applied in the lab test.

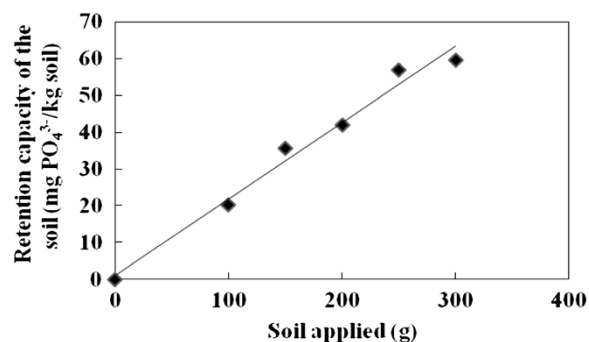


Figure 6 Phosphate retention capacity at different amounts (grams) of soil applied.

depths after the artificial rainfall events (six times) depending on the resources applied. Coefficients of permeability of the soil were 4.51×10^{-3} cm/s for LF and 3.56×10^{-3} cm/s for CM after the six rainfall events. In the test with CM applied, the TN and TP concentrations were the highest on the top of the column, decreasing thereafter. In other words, most of the nutrients of CM were residual on the soil surface. In the case of LF, the TN variation showed a similar tendency to that of CM, but this was a comparatively small difference resulting from the physical characteristics of the resource. The liquid phase of nitrogen has more potential for leaching. Most of the phosphorus was retained in the soil, resulting from the adsorption mechanism (Ye et al. 2006) in both cases.

Phosphorus adsorption capacity

The soil used in this study was coarse sand with low electrical property; therefore, the effect of this sand was ignored for soil adsorption capacity. The phosphorus adsorption capacity was examined using a PO_4^{3-} standard solution with 50 g of soil/100 mL of liquid. Phosphate adsorption could be affected by the increased pH (Ye et al. 2006). The pH of the soil examined in this study was 6.7, thereby the effect of the pH of soil on the phosphate adsorption was neglected. The maximum adsorption capacity was observed as 2.1 mg PO_4^{3-} /kg of soil (0.7 mg P/kg of soil), and the maximum removal efficiency was 82% (Figure 5). The corresponding phosphate concentration applied was 1.3 mg/L. The removal efficiency was decreased as the phosphorus was saturated in the soil.

LF was examined as an adsorbent at different amounts (grams) of soil. The soil to liquid ratios applied were 1:3, 1:2, 1:1.5, 1:1.2, and 1:1. The average retention capacity of the soil was 22 mg P/kg of soil. The linear regression coefficient was $r^2 = 0.98$ (Figure 6). The retention degree of the P was 60% with 300 g of soil applied. The P retention capacity of soil is essential for proper management of P addition to soil (Lge et al. 2005). The retention capacity of soil could be dependent on the soil physico-chemical properties such as soil texture and soil pH.

Conclusions

Total nitrogen was decreased by a repeatable artificial rainfall event, and the nitrate concentration in ground-water was gradually increased in the field examination. This result was prominent with pig liquid fertilizer. Phosphorus was mostly adsorbed in the soil, and its reduction was mainly affected by the soil drainage from surface runoff in summer. Soil adsorption and retention capacity would be important factors for the optimum level of nutrient application that is required

for agricultural performance and minimal environmental impact.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

All authors, YL and SO, have made adequate effort on all parts of the work necessary for the development of this manuscript. Both authors read and approved the final manuscript.

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